PHYS-3301

Lecture 4

Sep. 6, 2018

CHAPTER 3
The Experimental Basis of Quantum Physics

- 3.1 Discovery of the X Ray and the Electron
- 3.2 Determination of Electron Charge
- 3.3 Line Spectra
- 3.4 Quantization
- 3.5 Blackbody Radiation (Plank; 1900; 1918*)
- 3.6 Photoelectric Effect (Einstein; 1905; 1921*)
- 3.7 X-Ray Production (Röntgen;1895; 1901*)
- 3.8 Compton Effect (Compton; 1927; 1927*)
- 3.9 Pair Production and Annihilation (Anderson; 1932; 1936*)

The Planck's Black-Body Radiation Law:

The Energy (*E*) in the electromagnetic radiation at a given frequency (*f*) may take on values restricted to

$$E = nhf$$

where:

n = an integer

h = a constant $h \approx 6.626 \times 10^{-34} J \cdot s$

("Planck Constant")

Experimental Fact:

$$E = nhf$$

BUT Why should the energy of an Electromagnetic wave be "Quantized"? (n= integer)

No Explanation until 1905

Albert Einstein

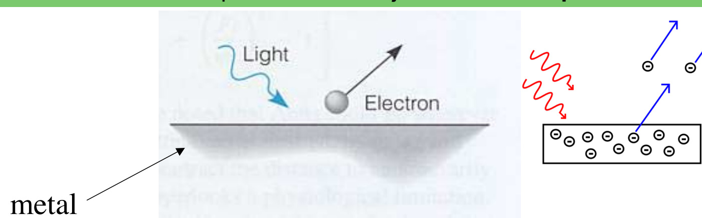
The Photoelectric Effect

A wave is a Continuous Phenomenon ?

3.6: Photoelectric Effect

The Photoelectric Effect
(Albert Einstein 1905)

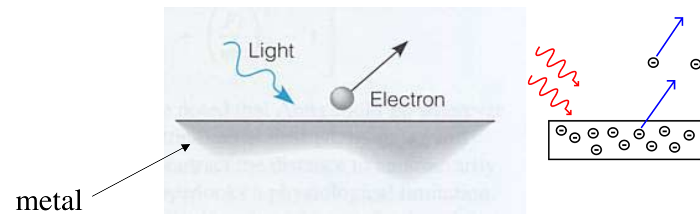
Electromagnetic radiation interacts with electrons within metals and gives the electrons increased kinetic energy. Light can give electrons enough extra kinetic energy to allow them to escape. We call the ejected electrons **photoelectrons**.



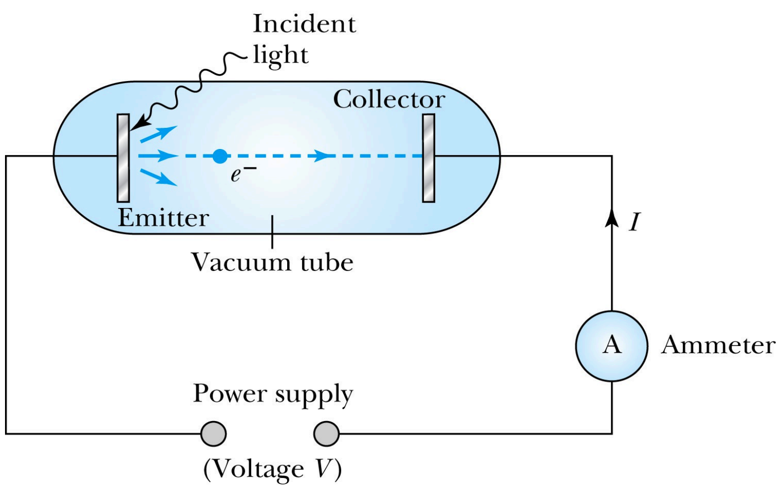
3.6: Photoelectric Effect

The Photoelectric Effect
(Albert Einstein 1905)

Albert Einstein postulated the existence of quanta of light -- **photons** -- which, when absorbed by an electron near the surface of a material, could give the electron enough energy to escape from the material.

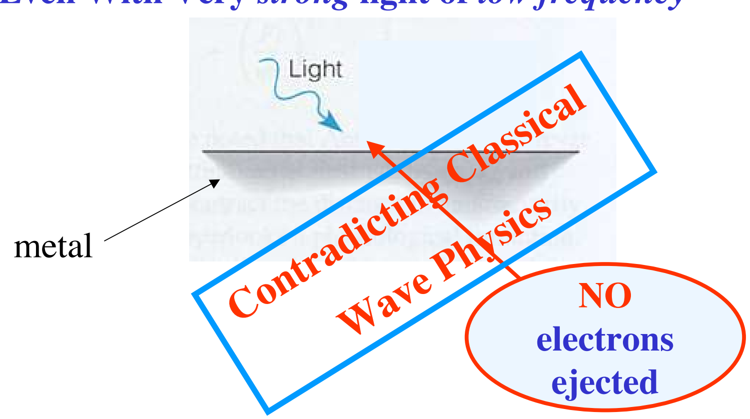


Experimental Setup



The Photoelectric Effect
(Albert Einstein 1905)

Even With Very *strong* light of *low frequency*

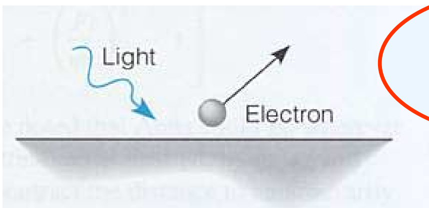


The Photoelectric Effect

(Albert Einstein 1905)

Even With Very-Very *weak* light intensity,

but of *high enough frequency*



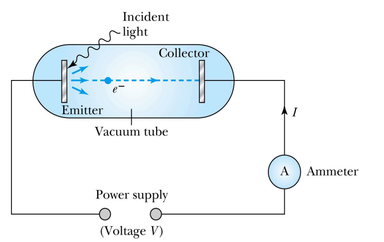
Electrons ejected

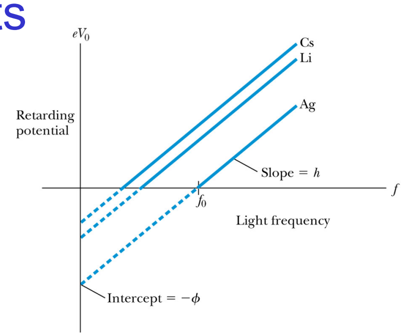
- Classical theory would predict that for extremely low light intensities, a long time would elapse before any one electron could obtain sufficient energy to escape. We observe, however, that the photoelectrons are ejected almost immediately.

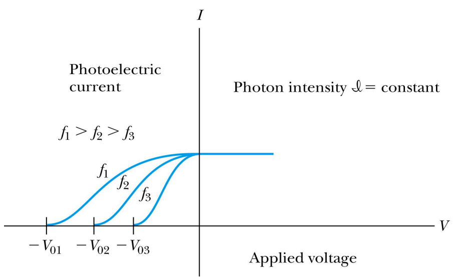
Experimental Results

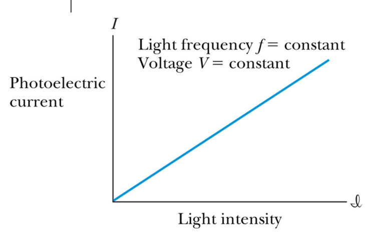
1) The kinetic energies of the photoelectrons are independent of the light intensity. ???
2) The maximum kinetic energy of the photoelectrons, for a given emitting material, depends only on the frequency of the light. ???
3) The smaller the work function φ of the emitter material, the smaller is the threshold frequency of the light that can eject photoelectrons. ???
4) When the photoelectrons are produced, however, their number is proportional to the intensity of light. ???
5) The photoelectrons are emitted almost instantly following illumination of the photocathode, independent of the intensity of the light. ???

Experimental Results









Einstein's Theory

- Einstein suggested that the electromagnetic radiation field is quantized into particles called **photons**. Each photon has the energy quantum:

$$E = hf$$

where f is the frequency of the light and h is Planck's constant.

- The photon travels at the speed of light in a vacuum, and its wavelength is given by

$$\lambda f = c$$

Planck's Law
($E = nhf$)

Photoelectric Effect
(Threshold frequency)

Albert Einstein
proposed:

The light is behaving as a collection of *particles* called *"photons"* each of them having energy

$$E = hf$$

The Photoelectric Effect

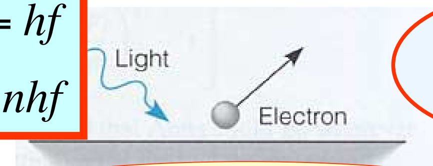
(Albert Einstein 1905)

Even With Very-Very *weak* light intensity,

but of *high enough frequency*

$$E_{photon} = hf$$

$$E_{beam} = nhf$$



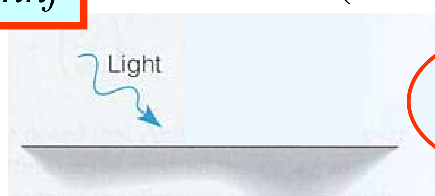
Electrons ejected

What happens is that 1 PHOTON ejects 1 ELECTRON

Example (1): Very intensive light beam, low frequency light

$E_{photon} = hf$ ← **SMALL (below the threshold)**

$E_{beam} = nhf$ ← **LARGE (n is large)**



NO Electrons ejected

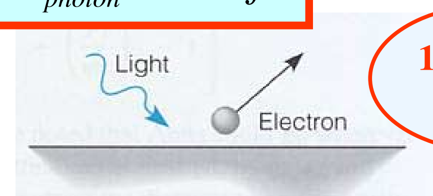
There is no PHOTON capable of ejecting an ELECTRON

Example (2): SINGLE PHOTON

Very weak light beam of high frequency

$E_{photon} = hf$ ← **LARGE (above the threshold)**

$$E_{beam} = E_{photon} = nhf$$



1 electron ejected

The PHOTON ejects 1 ELECTRON

Einstein's Theory

- Conservation of energy yields:

$$\text{Energy before (photon)} = \text{energy after (electron)}$$
$$hf = \phi + \text{K.E. (electron)}$$

where ϕ is the work function of the metal
Explicitly the energy is

$$hf = \phi + \tfrac{1}{2} m v_{max}^2$$

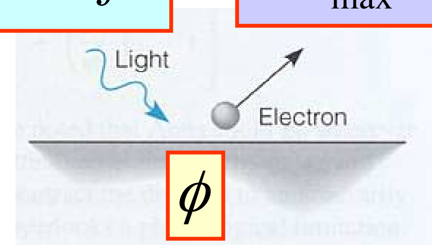
- The retarding potentials measured in the photoelectric effect are the opposing potentials needed to stop the most energetic electrons.

$$eV_0 = \tfrac{1}{2} m v_{max}^2$$

Energy Conservation:

$$E_{photon} = hf$$

$$KE_{max} = hf - \phi$$



ϕ

Also known at that time:

Metal	Work Function ϕ (in eV)
Potassium	2.2
Sodium	2.3
Magnesium	3.7
Zinc	4.3
Chromium	4.4
Tungsten	4.5

To free an electron from the metal, one has to "pay" a certain amount of energy

the *Work Function*

Quantum Interpretation

- The kinetic energy of the electron does not depend on the light intensity at all, but only on the light frequency and the work function of the material.

$$\frac{1}{2} m v_{max}^2 = eV_0 = hf - \phi$$

- Einstein in 1905 predicted that the stopping potential was linearly proportional to the light frequency, with a slope *h*, the same constant found by Planck.

$$eV_0 = \frac{1}{2} m v_{max}^2 = hf - hf_0 = h(f - f_0)$$

- From this, Einstein concluded that light is a particle with energy:

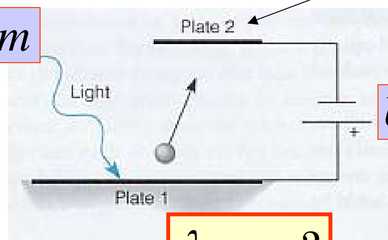
$$E = hf = \frac{hc}{\lambda}$$

Example 2.1

Light of 380-nm wavelength is directed at a metal plate, plate 1 (Figure 2.1). To determine the energy of electrons ejected, a second metal plate, plate 2, is placed parallel to the first, and a potential difference is established between them. Photoelectrons ejected from plate 1 are found to reach plate 2 as long as the potential difference is no greater than 2.00 V. Determine (a) the work function of the metal, and (b) the maximum-wavelength light that can eject electrons from this metal.

Repels electrons

$\lambda = 380nm$

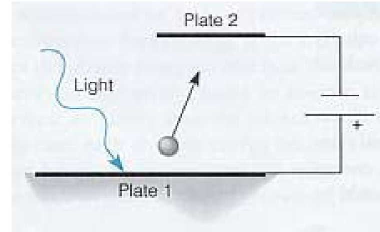


$U < 2Volts$

$\phi = ?$

$\lambda_{max} = ?$

$f_{min} = ?$



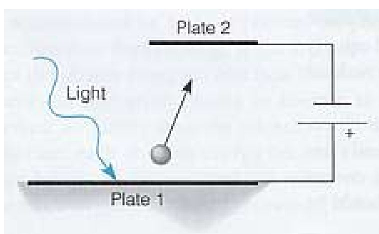
$KE_{max} = hf - \phi$

Solution

- Electrons are ejected from plate 1 with a certain max. KE.
- If none have enough KE to surmount the electrostatic PE difference (qV), no electrons will reach place 2.
- qV ((=1.6x10^{-19} C) (2V) = 3.2 x 10^{-19} J = 2 eV) is the max. that can be surmounted, so the max KE must be 2 eV.
- Using the equation,

$$3.20 \times 10^{-19}\text{ J} = (6.63 \times 10^{-34}\text{ J·s})\left(\frac{3 \times 10^{8}\text{ m/s}}{380 \times 10^{-9}\text{ m}}\right) - \phi$$

$$\Rightarrow \quad \phi = 2.03 \times 10^{-19}\text{ J} = 1.27\text{ eV}$$



- **Determine the max. wavelength (λ') light that can eject electrons from this metal.**
- **The limit of ejecting electrons occurs when an incoming photon has only enough energy to free an electron from the metal, with none left for KE.**

$$0 = hf' - \phi = (6.63 \times 10^{-34}\text{ J·s})\left(\frac{3 \times 10^{8}\text{ m/s}}{\lambda'}\right) - 2.03 \times 10^{-19}\text{ J}$$

$$\Rightarrow \quad \lambda' = 978\text{ nm}$$

Problems

1. The work function of tungsten surface is 5.4eV. When the surface is illuminated by light of wavelength 175nm, the maximum photoelectron energy is 1.7eV. Find Planck's constant from these data.

$$K_e = hf - W = h\frac{c}{\lambda} - W$$

Problems

1. The work function of tungsten surface is 5.4eV. When the surface is illuminated by light of wavelength 175nm, the maximum photoelectron energy is 1.7eV. Find Planck's constant from these data.

$$K_e = hf - W = h\frac{c}{\lambda} - W \qquad h = \frac{(K_e + W)\lambda}{c} = \frac{(1.7eV + 5.4eV)\times 1.75\times10^{-7}m}{3\times10^{8}m/s} = 4.1\times10^{-15}eV\cdot s$$

$$= 4.1\times10^{-15}eV\cdot s \times 1.6\times10^{-19}J/eV = 6.6\times10^{-34}J\cdot s$$

2. The threshold wavelength for emission of electrons from a given metal surface is 380nm.
(a) what will be the max kinetic energy of ejected electrons when λ is changed to 240nm?
(b) what is the maximum electron speed?

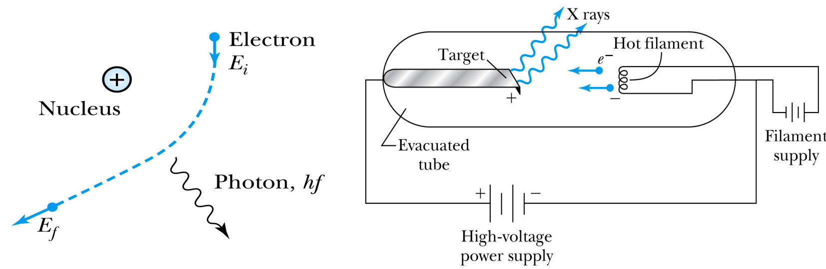
(a) $$h\frac{c}{\lambda_0} = W \qquad K_e = h\frac{c}{\lambda_1} - W = h\frac{c}{\lambda_1} - h\frac{c}{\lambda_0} = hc\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_0}\right) = 1.9eV$$

(b) $$K_e = m_e v^2/2 \qquad v = \sqrt{\frac{2K_e}{m_e}} = 8.2\times10^{5}m/s$$

3.7: X-Ray Production

(The "opposite" of the Photoelectric Effect)

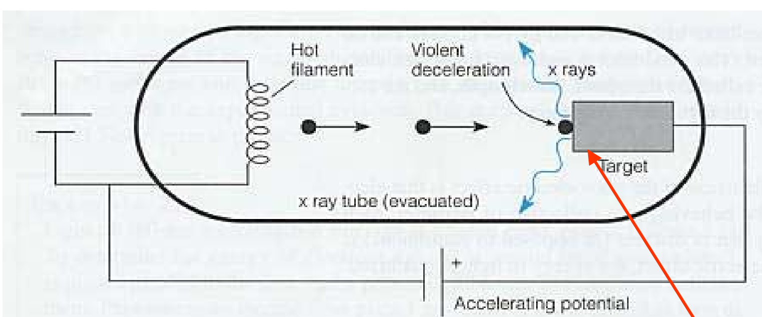
- An energetic electron passing through matter will radiate photons and lose kinetic energy which is called **bremsstrahlung**, from the German word for "braking radiation." Since linear momentum must be conserved, the nucleus absorbs very little energy, and it is ignored. The final energy of the electron is determined from the conservation of energy to be $E_f = E_i - hf$
- An electron that loses a large amount of energy will produce an X-ray photon.



X-rays can be produced by smashing high-speed electrons into a metal target. When they hit, these decelerating charge produce much radiation

The Production of X-Rays (Wilhelm Roentgen 1901)

(The "reverse" of the Photoelectric Effect)



Photon = wave

CLASSICAL physics:
Radiation covers entire spectrum

Bremsstrahlung

SURPRISE:

Experiments indicate a cutoff wavelength:

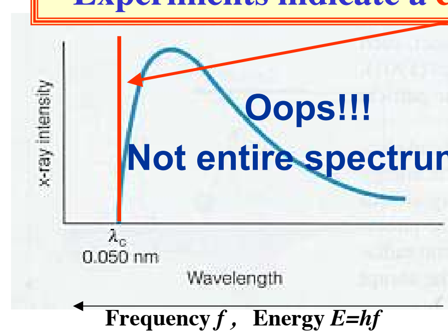


Figure 2.3 The x-ray spectrum produced when 25-keV electrons strike a molybdenum target.

There is no classical explanation for so sharp a termination of the spectrum

Inverse process

1 photon -> 1 electron
(?) 1 electron -> 1 photon (?)

SURPRISE:

Experiments indicate a cutoff wavelength:

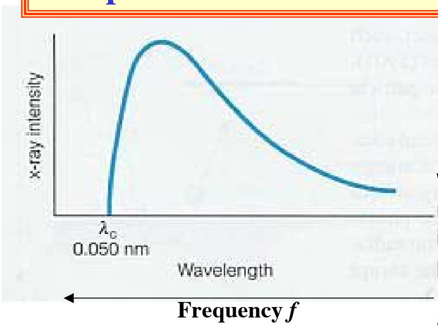


Figure 2.3 The x-ray spectrum produced when 25-keV electrons strike a molybdenum target.

If the radiation is quantized, the minimum E allowed at f is "hf" (single photon). We can't produce half a photon, so if multiple electrons don't combine their Es into a single photon, no photon could be produced of E > KE of a single electrons.

Setting the KE of an incoming electron = E of one photon

INDEED:

$$25\ \text{keV} = h\frac{c}{\lambda}$$

$$\Rightarrow \quad \lambda = \frac{(6.63 \times 10^{-34}\ \text{J·s})(3 \times 10^{8}\ \text{m/s})}{(25 \times 10^{3}\ \text{eV})(1.6 \times 10^{-19}\ \text{J/eV})} = 5.0 \times 10^{-11}\ \text{m} = 0.050\ \text{nm}$$

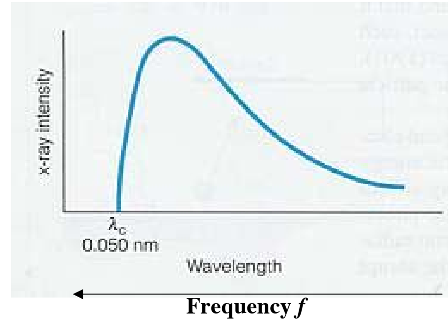


Figure 2.3 The x-ray spectrum produced when 25-keV electrons strike a molybdenum target.

INDEED:

1 electron -> 1 photon

Inverse Photoelectric Effect.

- Conservation of energy requires that the electron kinetic energy equal the maximum photon energy where we neglect the work function because it is normally so small compared to the potential energy of the electron. This yields the **Duane-Hunt limit** which was first found experimentally. The photon wavelength depends only on the accelerating voltage and is the same for all targets.

$$eV_0 = hf_{\max} = \frac{hc}{\lambda_{\min}}$$

$$\lambda_{\min} = \frac{hc}{e}\frac{1}{V_0} = \frac{1.240\times10^{-6}\ \text{V}\cdot\text{m}}{V_0}$$